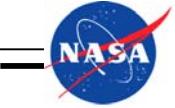


Orbit Determination Results and Trajectory Reconstruction for the Cassini/Huygens Mission

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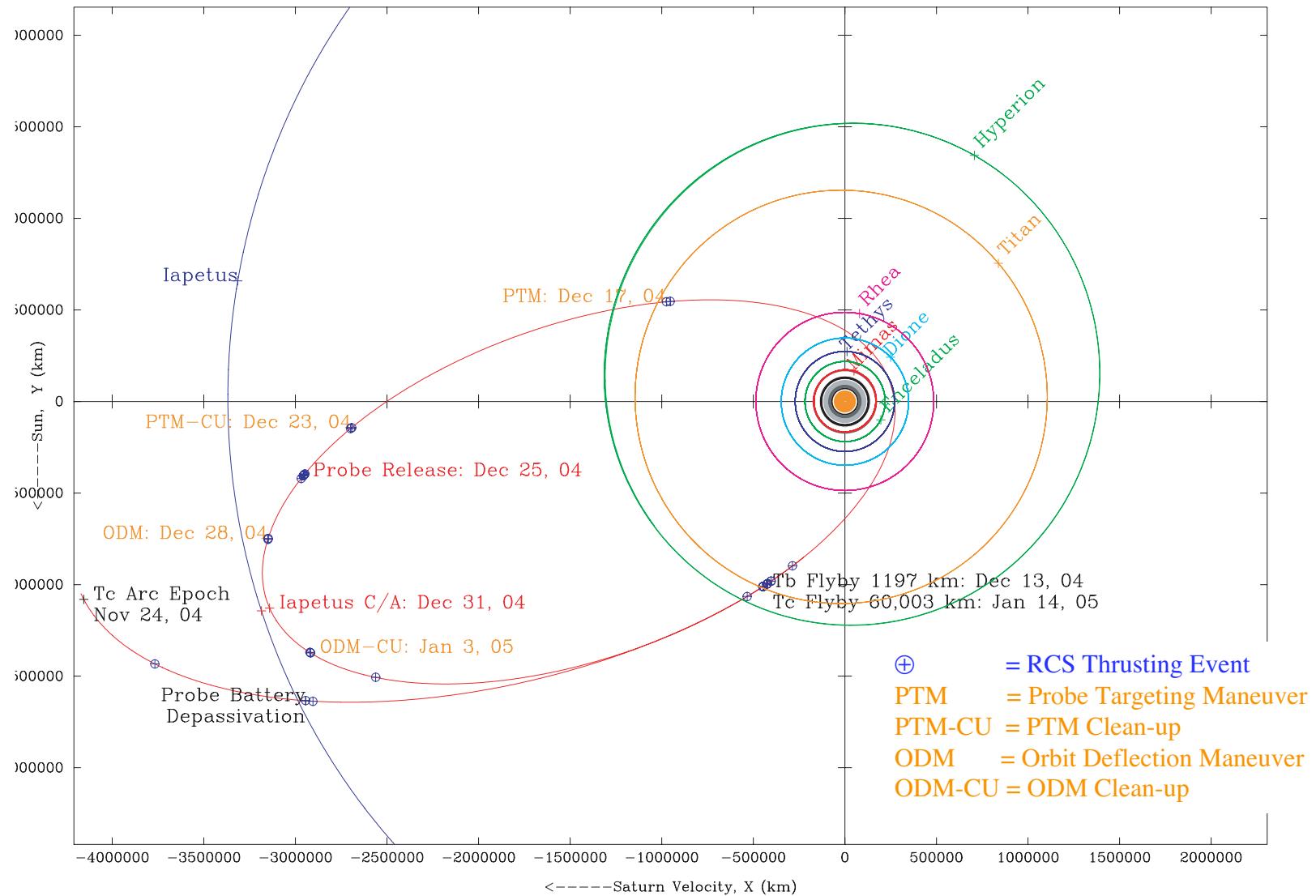
3rd International Planetary Probe Workshop
27 June, 2005
Anavyssos, Attica, Greece



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Trajectory Diagram

North Saturn Pole View

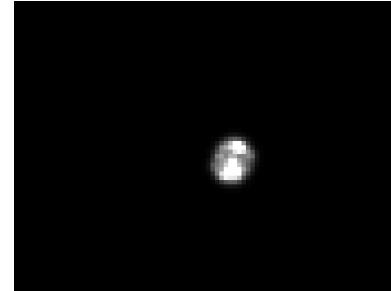


Requirements

- Navigation was required to deliver the Huygens probe to the interface altitude (1270 km) at the interface time (14-Jan-2005 9:07 ET) with the following constraint:
 - Flight Path Angle: $-65^\circ \pm 3^\circ$ (99%)
- Requirement for the Navigation contribution of the orbiter-to-probe pointing accuracy during the probe relay to be less than 3.0 mrad (99%)

Tracking Data

- Radio Metric Tracking (X-band Range and 2-way coherent Doppler)
 - Schedule
 - 1 pass/day before Tb flyby (the primary focus to collect science data)
 - 1.5 day gap in tracking for the Tb flyby
 - 2 pass/day after Tb flyby (the primary focus to accurately delivery the probe)
 - Pass-by-pass weighting based on the RMS of residuals
 - Post-fit Doppler RMS = 0.02 mm/s (1-minute compression)
 - Post-fit Range RMS = 0.4 m (5-minute integration time)
- Optical Navigation Images (OpNavs)
 - 103 OpNavs of the 8 major satellites taken between Nov 24 and Dec 27
 - Satellite Weights dependent on target satellite and range to satellite
 - Post-fit RMS = 0.8 pixels
- Three sets of probe images were obtained between separation and the Orbit Deflection Maneuver (ODM)
 - Weights: 0.25 to 1.0 pixels



Parameters that had to be Estimated

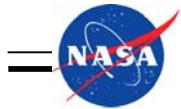
- 178 Estimated Parameters:
 - Orbiter/Probe Epoch State
 - Constant acceleration in each spacecraft fixed direction
 - 4 maneuvers (PTM, PTM-cu, ODM, & ODM-cu)
 - ΔV Magnitude, Right Ascension, Declination, & Start time for each maneuver
 - Probe release - modeled as an impulsive maneuver
 - Cartesian components of the Orbiter ΔV are estimated
 - Cartesian components of the Probe ΔV are forced to be equal to the orbiter ΔV estimate, scaled by the mass ratio between the orbiter and the probe
 - Stochastic accelerations: Batch time & a priori uncertainty varies depending on amount of spacecraft activity
 - 28 small forces (RCS thrusting events)
 - 8 satellite states and GMs
 - Saturn state, GM, J2, J4, and Pole
 - Range biases: Global station biases and per pass biases
 - Camera pointing corrections per OpNav
 - Titan OpNav phase biases (0th and 1st order)
- Considered Errors (not estimated):
 - Station locations
 - Media Calibrations
 - Polar motion

Covariance Study Results

- In preparation for the Huygens mission, covariance studies were performed to make sure that the flight path angle requirement of $-65^\circ \pm 1.15^\circ$ (1-sigma) would be met
 - During this time, the ongoing estimates for the GM of Iapetus were making multi-sigma changes
 - The altitude of the Iapetus flyby after separation was raised from 64,000 km to 127,000 km, increasing the acceptable Iapetus GM error from $1.5 \text{ km}^2/\text{s}^3$ to $7.2 \text{ km}^2/\text{s}^3$

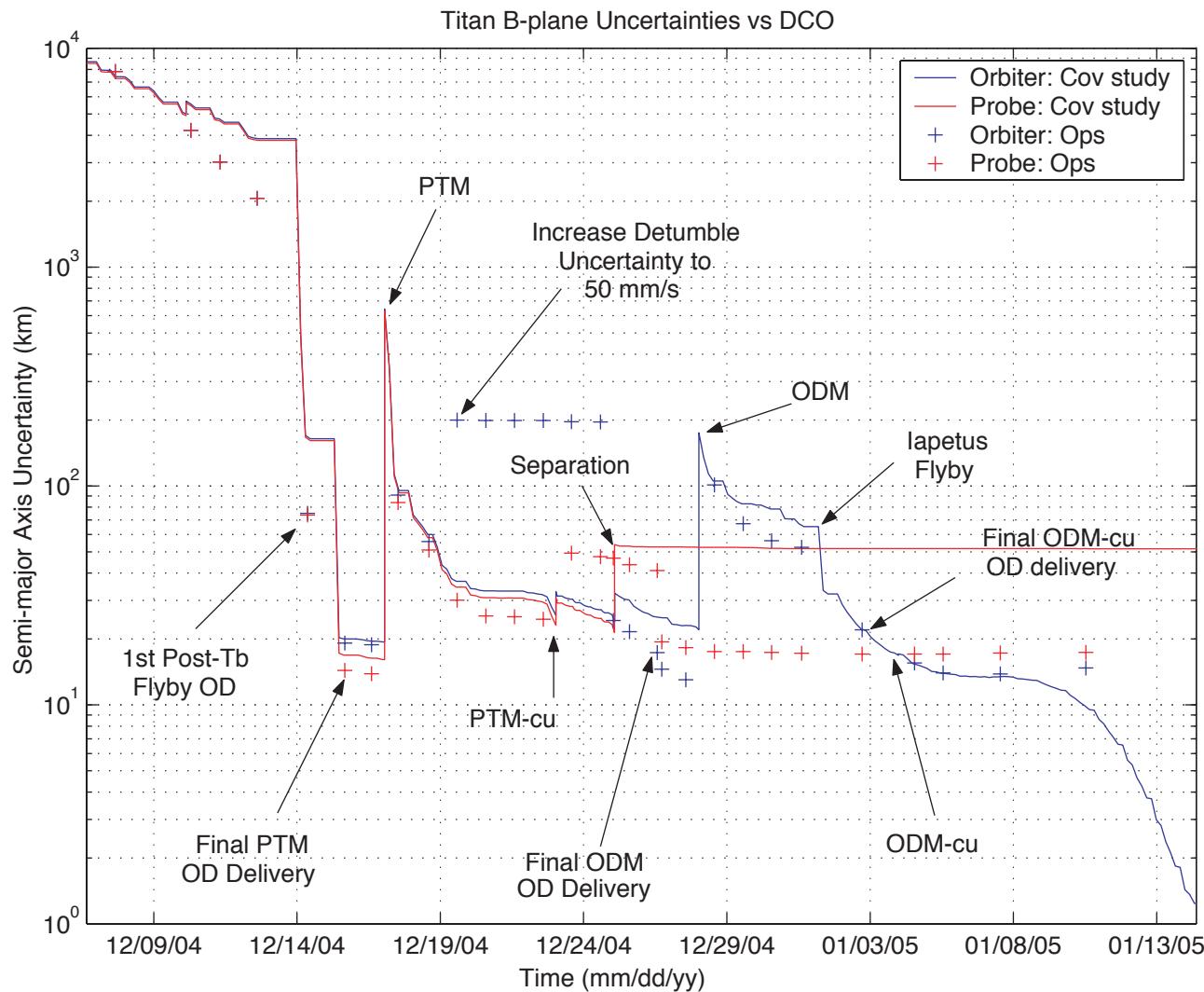
Probe Flight Path Angle Error Budget (1-sigma):

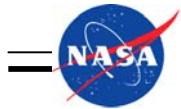
Error Source	Contribution (deg)	
Separation (x,y,z = 12 mm/s)	0.74	
PTM-cu execution errors	0.31	
RCS Thrusting Events	0.23	
Stochastic Accelerations	0.23	
OpNav Noise	0.19	
RTG Acceleration	0.10	
Saturn & Satellite ephemeris	0.08	Results shown for PTM-cu data
PTM execution errors	0.08	cutoff @ 21-Dec-2004 14:00 (about
Radiometric Noise	0.05	35 hours prior to maneuver)
S/C state a priori uncertainty	0.04	
Earth Orientation Parameters	0.03	
Tb approach maneuver	0.02	
Media calibration uncertainties	0.02	
Range biases	0.02	
Station Locations	0.01	
OpNav pointing uncertainty	0.00	
Titan Phase biases	0.00	
RSS	0.90	



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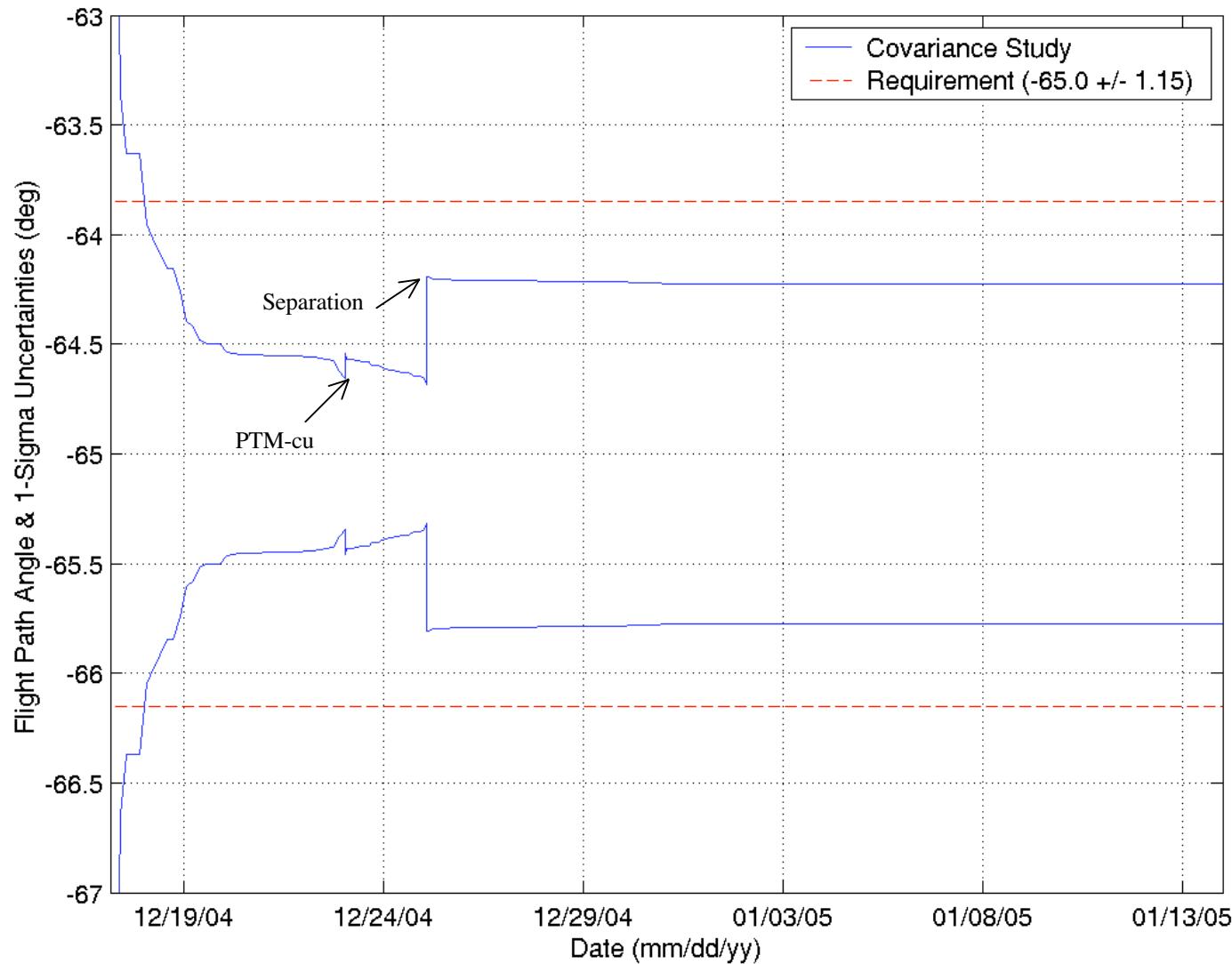
Predicted vs Actual Uncertainties

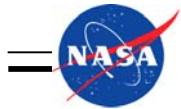




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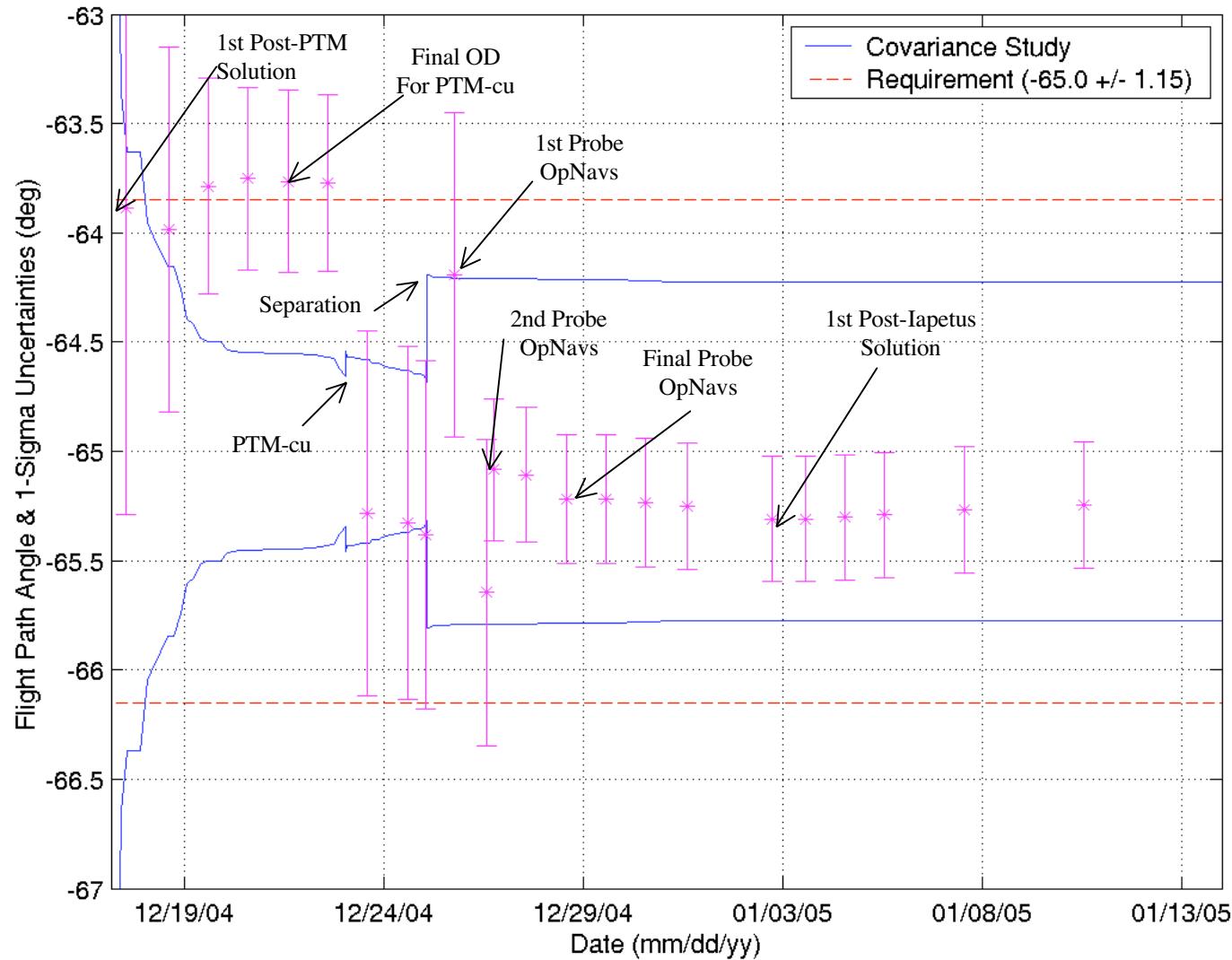
Flight Path Angle Predictions

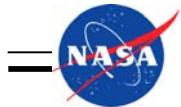




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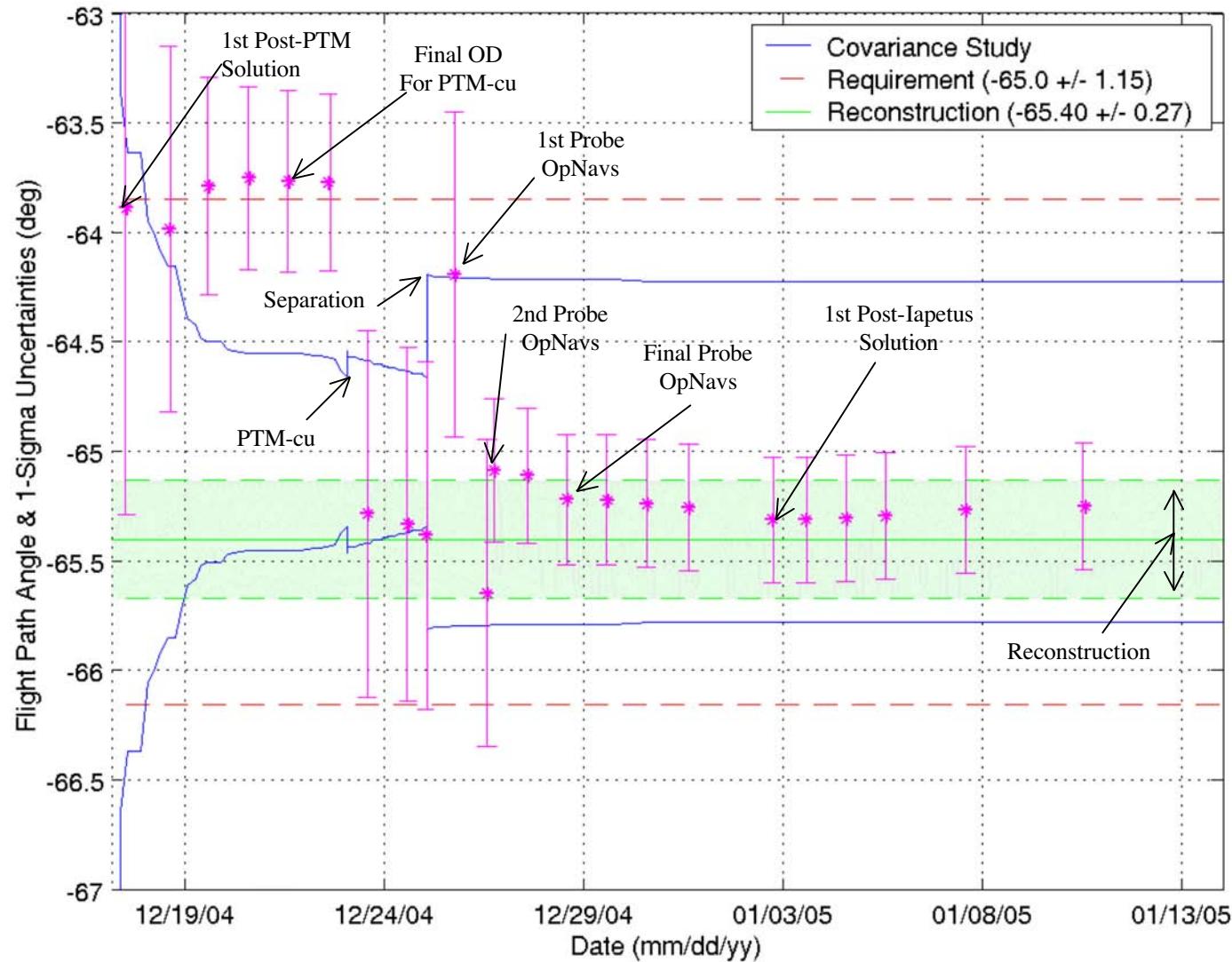
Flight Path Angle Solutions

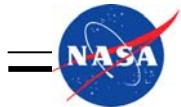




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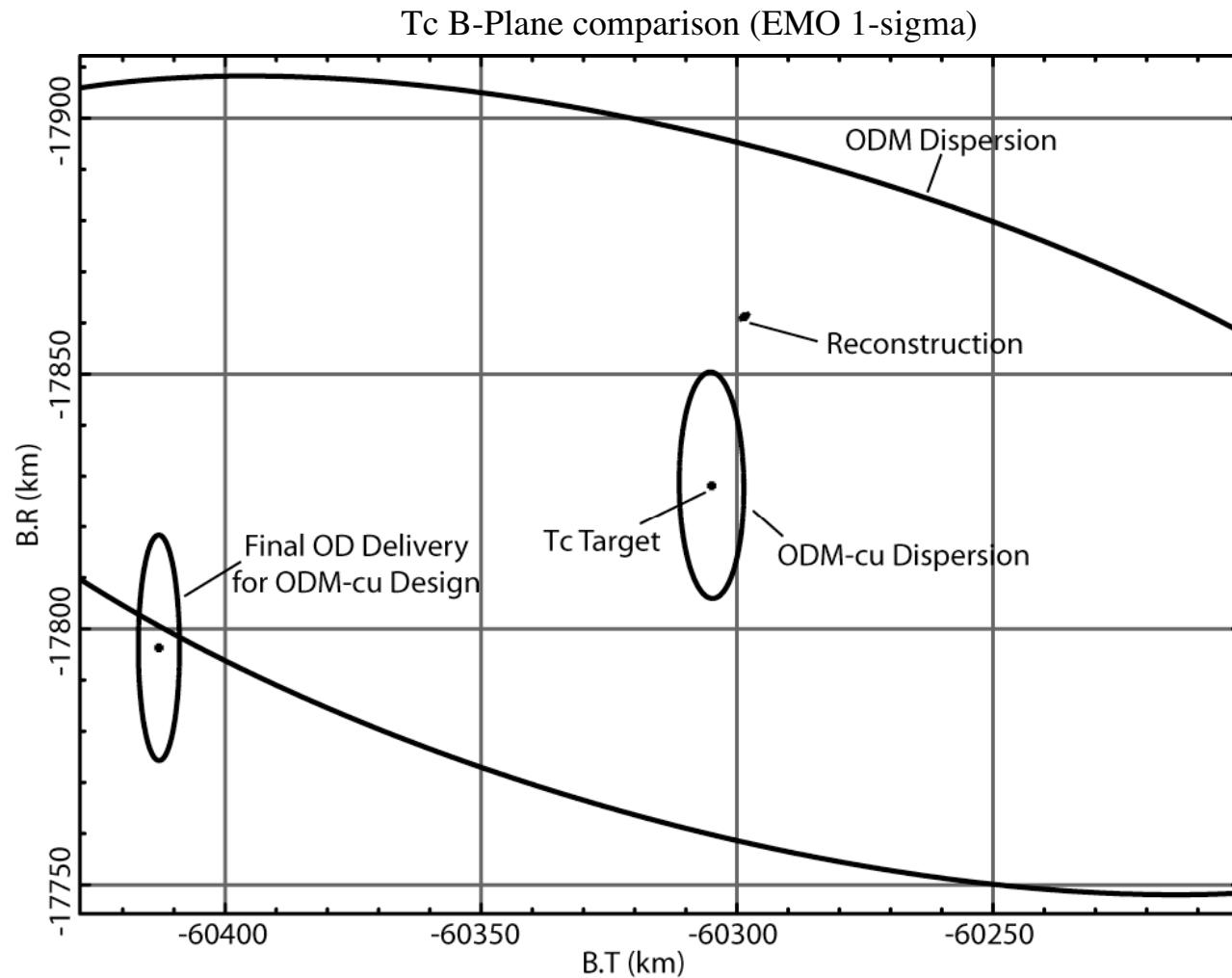
Flight Path Angle Reconstruction



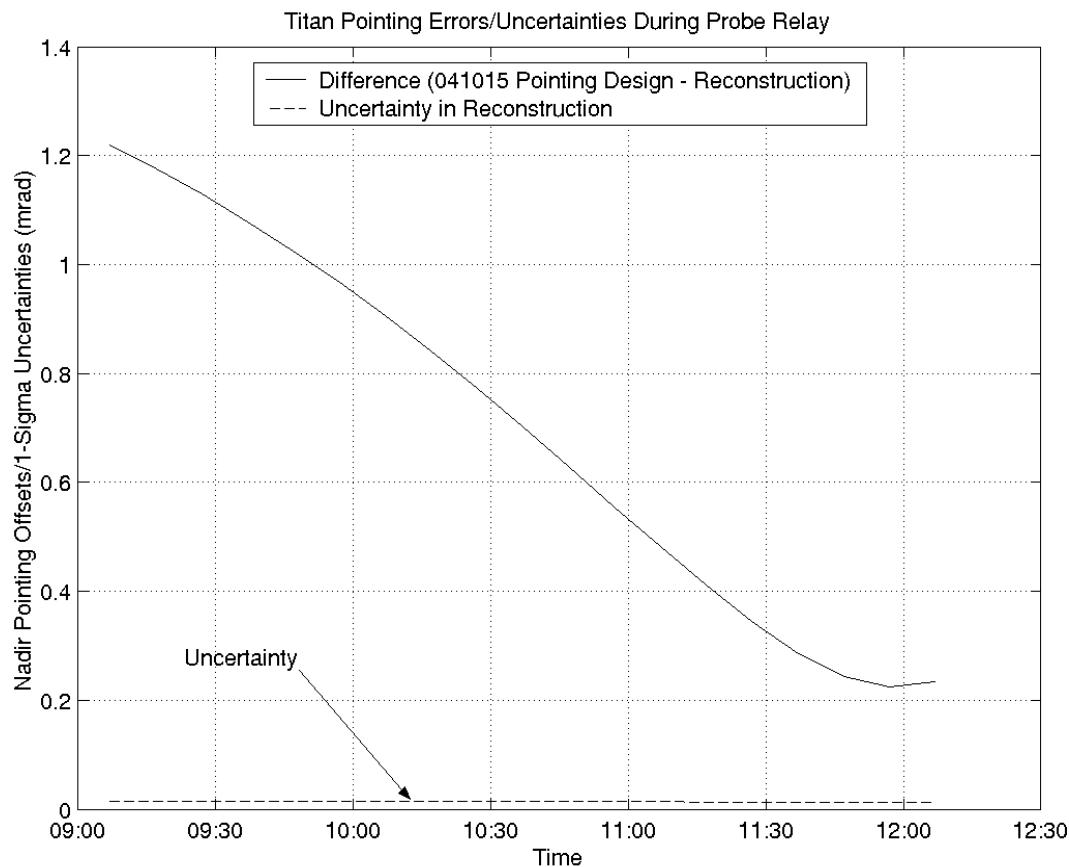


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Titan-C Flyby Results



Probe Relay Pointing Results



- a) The Navigation induced Cassini-to-Titan pointing errors are due to differences between the ephemerides used to build the on-board pointing parameters and the reconstructed ephemerides.
- b) The requirement that the Navigation induced pointing errors be less than 3.0 mrad was clearly met.

Conclusions

- The Navigation in support of the Huygens probe mission was completely successful
 - The probe flight path angle was well within the required corridor
 - The probe relay pointing errors were significantly smaller than required
- The Covariance studies were a reliable and valuable tool
 - They provided insight into the contribution of the various error sources
 - They provided the impetus to increase the altitude of the Iapetus flyby
 - They were valuable as a comparison during operations
- The probe OpNavs were effective in helping to provide separation between the release ΔV and detumble ΔV estimates, resulting in a more certain estimate of the probe flight path angle